Epitaxial Growth III

Simulation of the Large-area Growth of Homo-epitaxial 4H-SiC by Chemical Vapor Deposition
M. Pons[1], J. Meziere[1], J. Dedulle[1], S. Wan Tang Kuan[2], E. Blanquet[1], P. Ferret[2], L. Di Coccio[2], T. Billon[2], R. Madar[1]
[1]INP Grenoble, France; [2]CEA/LETI Grenoble, France

Predicting Growth Rates of SiC Epitaxial Layers Grown by Hot-wall Chemical Vapor Deposition
Ö. Danielsson, S. Jonnson, A. Henry, E. Janzén
Linköping University, Sweden

Characteristics of Boron in 4H-SiC Layers Produced by High-Temperature Techniques
A. Kakanakova-Georgiev, R. Yakimova, J. Zhang, M. Syväyärvi, E. Janzén
Linköping University, Sweden

Impact of the Initial Surface Conditions on the Defect Appearance in 4H-SiC Epilayers
R. Yakimova, H. Jacobson, Syväyärvi, A. Kakanakova-Georgiev, T. Iakimov, C. Virojanadar, L. Johansson, E. Janzén
Linköping University, Sweden

Highly Uniform Epitaxial SiC Layers Grown in a Hot Wall CVD Reactor with Mechanical Rotation
A. Schöner[1], A. Konstantinov[1], S. Karlsson[2], R. Berge[3]
[1]ACREO AB, Sweden; [2]ADC, Sweden; [3]Epigress AB, Sweden

Fast Epitaxial Growth of 4H-SiC by Chimney-Type Hot-Wall CVD
K. Fujihira, T. Kimoto, H. Matsunami
Kyoto University, Japan

Growth and Electrical Characterization of the Low-Doped Thick 4H-SiC Epilayers
H. Tsuchida, I. Kamata, T. Jikimoto, K. Izumi
Central Research Institute of Electric Power Industry, Japan

High-Rate Epitaxial Growth of 4H-SiC Using a Vertical-Type, Quasi-Hot-Wall CVD Reactor
K. Masahara[1,3], T. Takahashi[2,3], M. Kushibe[1,3], T. Ohno[1,3], J. Nishio[1,3], K. Kojima[1,2,3], Y. Ishida[2,3], T. Suzuki[1,3], T. Tanaka[1,3], S. Yoshida[2,3], K. Arai[2,3]
[1]R&D Association for Future Electron Devices, Japan; [2]National Institute of Advanced Industrial Science and Technology, Japan; [3]Ultra-Low-Loss Power Device Technology Research Body, Japan

Simulation of the large-area growth of homoepitaxial 4H-SiC by chemical vapor deposition

Michel Pons[1], Jerome Mezière[1], Jean Marc Dedulle[3], Stephane Wan Tang Kuan[2], Elisabeth Blanquet[1], Claude Bernard[1], Pierre Ferret[2], Lea Di Cioccio[2], Thierry Billon[2] and Roland Madar[3]

[1]LTPCM- UMR 5614 (CNRS/INPG/UJF), Domaine Universitaire, B.P.75, F-38402 St. Martin d'Hères Cedex, France; [2]LETI-CEA Grenoble, 38054 Grenoble Cedex 9, France; [3]LMGP - UMR 5628 (CNRS/INPG), Domaine Universitaire, B.P. 46, F-38402 St. Martin d'Hères Cedex, France

Telephone : 33 4 76826532 ; Fax : 33 4 76826677, E-mail : mpons@ltpcm.inpg.fr

1. INTRODUCTION

The SiC-base electronics applications have made tremendous progress primarily because of the commercial availability of SiC substrates of ever increasing diameter and quality. This triggers higher demands on the epitaxial process. The growth of thick epitaxial layers with low defect density and the control of the doping is an essential technique and the next step for the fabrication of devices. Our recent experimental and modelling work was recently applied to an horizontal hot-wall reactor commercially available from the Epigress company (http://www.epigress.se). Hydrogen is typically employed as the carrier gas along with silane and propane as precursor gases. Atmospheric and reduced pressures (10-100 kPa), temperature higher than 1700 K and C/Si ratios from 1 to 15 in the gas phase can be used. The quality, the growth rate and the doping level over 2" wafers are found to depend on the C/Si ratio in the gas phase supplied onto the growth surface, which suggests the importance of the intricate mixture of transport phenomena (heat and mass transfer) and reactivity.

2. SIMULATION

Thermodynamic and kinetic modelling were used to evaluate the qualitative influence of temperature, pressure and species reactivity on the deposition features. This approach is static (0D) at fixed pressure and temperature and it was difficult to give engineering conclusions. After the comparison of experiments with simulation trends in the 1700-2000 K temperature range and 25-100 kPa pressure range and many returns with simplified 2D simulations, we have decided to use a reduced and slightly modified version of the most complete and reliable heterogeneous and homogeneous kinetic database published. This reduced database includes 12 gaseous species (H_2, H, SiH_4, SiH_2, Si_2H_6, Si, C_3H_8, CH_3, C_2H_5, C_2H_6, C_2H_2, C_2H_4) and 5 surface species (Si_s, C_s, SiH_2_s, HC_s and HSi_s). The electromagnetic simulation has been performed on the hot-wall reactor in static conditions using Flux3D software package. It clearly shows that the rectangular shape of the susceptor associated with the cylindrical shape of the insulation leads to a 3D situation. The joule losses are higher in the lateral parts and consequently, the temperature is higher. A small part of the power is dissipated in the foam due to the striations. One of the drawbacks of this reactor is that the temperature along the susceptor is highly non-uniform. It is then difficult to process more than one wafer of 35-50 mm. The uniformity of the temperature distribution along the central 2/3 part of the susceptor can be slightly improved by increasing the thickness of the graphite (from 35 to 50 mm) and more by changing the position and the design of the coil. The next step is to combine iteratively this 3D simulation with heat and mass transfer.

The computation of the combined approach has been made for standard conditions using Cfdace software package and a series of user subroutines : P=25 kPa, T_{max}=1850 K, D_{H2}=80 l.min^{-1}, a C/Si ratio of 1 and a high dilution for precursors (from 1 to 6 10^{-4} in mole). The results show, for instance, that (i) gravity leads to a deposition on the top of the reactor at the exit of the susceptor (figure 1), (ii) the cold finger at the entrance of the susceptor contributes to non-uniform distributions of temperature (figure 2), (iii) deposition rate results from an intricate mixture of temperature and concentrations fields (figure 3) and (iii) that the main contributing gaseous species are SiH_2, Si, C_2H_2, C_2H_4 and CH_4. The model predict a rather good uniformity for the deposition rate, less than 10 %, for a wafer of 50 mm placed in the high temperature region (50 to 70 % of the susceptor length).

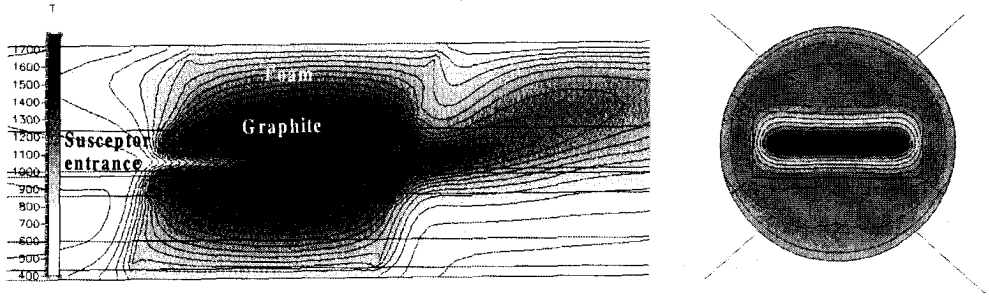

Figure 1. Influence of the gravity and of the narrow entrance of the susceptor on the temperature field for both an horizontal section (Z-cut at left) and a vertical section (X-cut at right) at the exit of the susceptor (P=25 kPa, T_{max}=1850 K, D_{H2}=80 l.min^{-1}, C/Si ratio =1 and 2 10^{-4} mole of SiH_4).

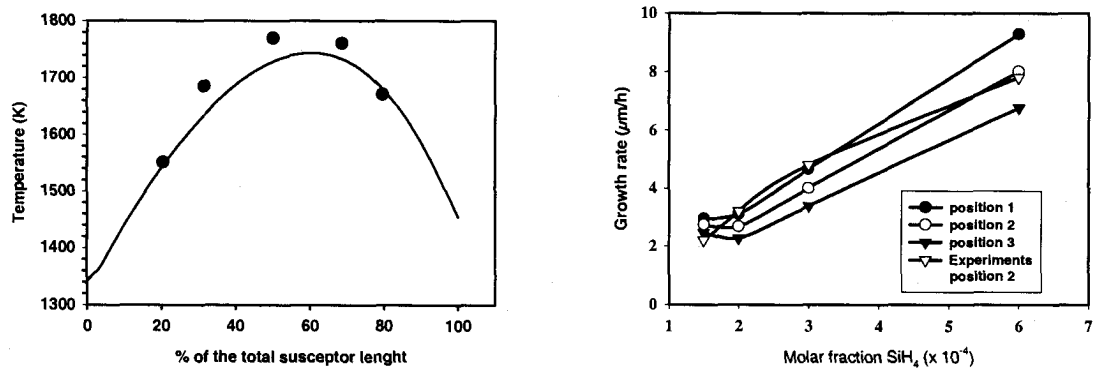

Figure 2. Comparison between the computed (—) and measured (•) temperature distribution along the centerline of the susceptor.

Figure 3. Evolution of the computed growth rate versus the molar fraction of silane (C/Si=1, temperature of figure 2) for 3 positions along the centerline of the wafer : position 1 is the leading edge, position 2 the center and position 3 the trailing edge of a single wafer located in the high temperature region of the susceptor.

In conclusion, it seems difficult to find a set of experimental parameters to process numerous wafers with a sufficient growth rate and uniformity in the standard version of this reactor. However, for a single wafer by run, high quality 4H-SiC films of 10 μm and devices have been processed. The residual doping is low (10^{14} cm^{-3}). This allows to process N-doped SiC layer when using small amount of nitrogen. We have found a non-linear dependence of the doping profile with the inverse of the initial propane flux and a strong dependence on the temperature. Hence, the production of thick 4H-SiC with low residual doping can be achieved with the hot-wall reactor used in this study. But, to reach a good doping uniformity improvements on the design of the deposition area are still needed.

Predicting growth rates of SiC epitaxial layers grown by hot-wall chemical vapor deposition

Ö. Danielsson*, S. Jönsson, A. Henry and E. Janzén

Department of Physics and Measurement Technology, Linköping University
SE – 581 83 Linköping, Sweden
**corresponding author: phone +46 13 28 2649 fax +46 13 14 2337 e-mail orjda@ifm.liu.se*

An important technology for growth of SiC epitaxial layers is the chemical vapor deposition (CVD) technique, which has been extensively studied in recent years, both experimentally [1, 2] and theoretically [3, 4, 5]. The growth of device quality epitaxial layers, such as MESFET structures, requires precise control of the thickness and doping uniformity and of the morphological quality. Optimizing and improving the CVD process is often expensive and time consuming. Simulations can be used to gain more understanding of the process, making development faster and less expensive. Modeling of the growth rate and morphology of epitaxial layers is an important step towards process optimization.
In order to obtain an accurate model for the growth, the chemistry involved has to be correctly modeled. Some models of gas phase and surface chemistry present in SiC CVD have been proposed [3, 5], however these models do not include the formation of organo-silicon species, which are believed to play an important role in the growth process [6]. Also, the proposed models have only predicted deposition rates and not deposit composition. The growth is either limited by the amount of carbon species or by the amount of silicon species available in the gas phase immediately above the growth surface. Thus, a precise model of the gas phase chemistry is essential to obtain accurate growth rate predictions. This work will use a new model, including some organo-silicon species, to simulate growth rates along the entire susceptor. To accurately predict the growth rate it is also crucial to know the exact temperature distribution inside the susceptor. Therefore the temperature inside the susceptor was both simulated three-dimensionally and measured by an in-situ method.

For the epitaxial growth a horizontal hot-wall type CVD reactor [1] was used. It consists of a hollow graphite susceptor surrounded by insulation inside an air cooled quartz tube. The graphite is inductively heated by a copper coil. Hydrogen (H_2) is used as carrier gas, silane (SiH_4) and propane (C_3H_8) as precursors. Growth was made on 10 mm wide stripes of 4H-SiC 8° off axis substrates, which were placed along the gas flow direction covering the whole susceptor length. Normal process parameters were C/Si = 3.5, T = 1600°C, H_2 gas flow = 13 slm, SiH_4 flow = 0.9 sccm and C_3H_8 flow = 1.05 sccm and atmospheric pressure. Different cases were studied, changing various process parameters such as pressure and carrier gas flow rate. The thickness of the deposited layers was measured by FTIR and the morphology was studied using optical microscopy. The doping was measured by CV and controlled with photoluminescence. The composition of the deposited material was studied using XPS in order to obtain a quantitative measurement of the precursor losses before the area of "good" growth. The results show an alternating carbon rich and silicon rich deposit at the entrance of the susceptor. The relative amount of silicon and carbon in the deposit on the first 20 mm of the susceptor for typical growth parameters is shown in Fig. 1. Different growth models are assigned to the boundaries of the simulation domain according to the results gained by XPS.
The carbon and silicon rich deposits are also confirmed by studies of the morphology by optical microscope, where certain types of surface defects can be attributed to carbon rich or

silicon rich growth. At the entrance of the susceptor there is a region of polycrystalline growth. Downstream from this region large triangular defects can be seen before the deposition turns into a completely mirror like surface, i.e. the useable growth area. Further downstream, towards the back of the susceptor, large triangular defects are again seen. When reducing the pressure, the polycrystalline region extends further inside the susceptor, but the transition to a completely mirror like surface does not show any triangular defects. The triangular defects on the surface are believed to originate from silicon rich deposition.

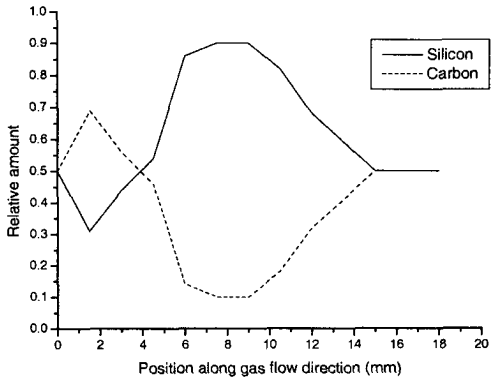

Fig. 1 The relative amount of silicon and carbon in the deposit on the first 20 mm of the susceptor (at 1000 mbar), as measured by XPS.

A slightly higher growth rate (about 10%) is observed for the reduced pressure growth compared to the growth at atmospheric pressure. This is also predicted by the simulations. The predicted and measured growth rates are shown in Fig. 2. In the figure a scaling factor has been used to compensate for the 2D effects caused by the axisymmetric approach used in the 2D simulations. Simulations were carried out for both 2D and 3D.

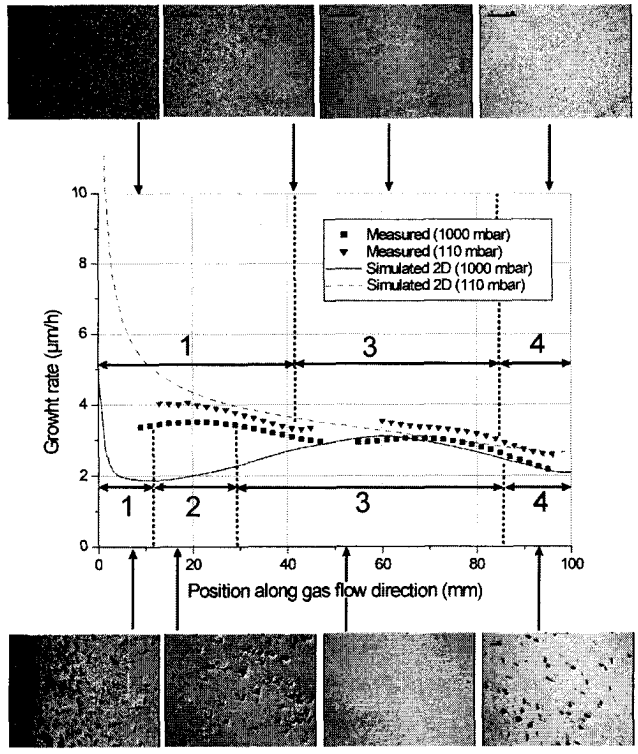

Fig. 2 Measured and predicted growth rates along the entire susceptor for two different pressures. The zones are indicating different types of growth; 1 – polycrystalline growth, 2 – triangular defects, 3 – usable growth area, 4 – defective surface.

Preliminary results from 3D simulations show good agreement with measured values.

[1] O. Kordina, C. Hallin, A. Henry, J.P. Bergman, I.G. Ivanov, A. Ellison, N.T. Son and E. Janzén, Phys. Stat. Sol. (b) **202** (1997), p. 321
[2] T. Kimoto, A. Itoh and H. Matsunami, Phys. Stat. Sol. (b) **202** (1997), p. 247
[3] M.D. Allendorf and R.J. Kee, J. Electrochem. Soc. **138** (1991) p. 841
[4] C.D. Stinespring and J.C. Wormhoudt, J. Crystal Growth, **87** (1988) p. 481
[5] F. de Jong and M. Meyyappan, Diamond Rel. Mat. **5** (1996) p. 141
[6] M.D. Allendorf, J. Electrochem. Soc. **140** (1993) p. 747

Characteristics of boron in 4H-SiC layers produced by high-temperature techniques

A. Kakanakova-Georgieva, R. Yakimova, J. Zhang, M. Syväjärvi, E. Janzén

Department of Physics and Measurement Technology, Linköping University, S-581 83 Linköping, Sweden,
tel: +46.13.282112; fax: +46.13.142337; e-mail: anelia@ifm.liu.se

Boron is a persistent residual impurity in SiC, especially when the growth process is performed at high (1600 – 1850°C) temperatures, which are typical in the sublimation epitaxy [1] and in the CVD epitaxy process in a vertical hot-wall ("chimney") reactor [2]. Both techniques are candidates for the growth of thick (> 30 μm) SiC layers for device applications like high-power switching, provided the demand on the material purity is satisfied. From this point of view investigations on different characteristics of B in 4H-SiC layers are important in order to establish growth parameters for controllable boron incorporation.

Boron, along with nitrogen and aluminum, can be present in as-grown sublimation epitaxy layers. The background impurities in the epilayers are unintentionally introduced from the growth environment, mainly the polycrystalline SiC source material and graphite. Boron incorporation (from $5x10^{15}$ cm^{-3} to $3x10^{17}$ cm^{-3}) in the layers can be affected by applying different growth temperatures that also change the growth rate (from 2 μm/h to 160 μm/h). The spectra in Fig. 1(a) present the cathodoluminescence (CL) signature of two layers with the same Al/N ratio and boron concentration of $(2 - 3)x10^{16}$ cm^{-3}. Formation of a strong green luminescence (GL) band at ~ 505 nm characterizes the layer produced at higher growth rate. The GL is believed to originate from deep boron centers [3].

Under CL excitation efficient GL (Fig. 1b) is recorded in the "chimney" grown epilayers characterized with B concentration below the SIMS detection limit (i.e. less than $5x10^{14}$ cm^{-3}) with a residual N doping in the range of mid 10^{13} cm^{-3}. The layers are obtained at growth rates of 15 – 25 μm/h, which is an order of magnitude higher than in the conventional CVD where no traces of GL are observed in the low doped layers. The finding that B atoms can cause strong GL even at small concentrations, provided B is introduced at higher growth rates, also holds for B residual doping in a "chimney" reactor.

We observe that the total boron concentration in the sublimation epitaxy layers and the intensity of GL related to the deep B centers increases, while the contribution from the B dopant to the net acceptor concentration, as measured by the mercury-probe CV technique, diminishes (Fig. 1c). The layers are fabricated at increasing growth rate. It has been argued that at high growth rates the Si/C ratio in the lattice increases especially if the growth rate is comparable or exceeds the rate of silicon and carbon self-diffusion [4]. As a consequence the concentration of C vacancies increases and thus gives rise to enhanced probability of forming the defect complexes considered to assist the deep B center formation, i.e. B_{Si}-V_C [5], B_{Si}-Si_C [6] or B_C [7]. Apparently, variations in the growth rate can cause redistribution between shallow and deep B-related centers, which cannot contribute to the acceptor concentration as measured by CV.

The results are further discussed in relation with the measurements done on "chimney" grown epilayers produced at growth rate of 20 μm/h and with varying the C/Si ratio.

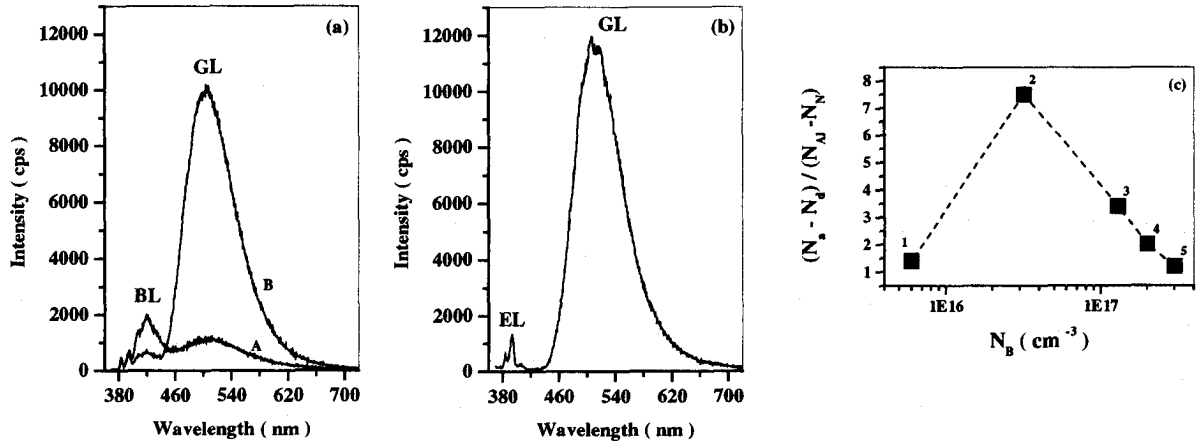

Fig. 1. *(a) CL spectra at 4.6 K of 4H-SiC sublimation epilayers produced at growth rate of 22 μm/h (A) and 160 μm/h (B). BL denotes blue luminescence at ~ 420 nm due to N-Al DAP recombination; (b) CL spectrum of a 4H-SiC "chimney" epilayer. EL denotes 4H-SiC edge luminescence starting near 380 nm; (c) The ratio of net acceptor concentration ($N_a - N_d$) to concentration difference ($N_{Al} - N_N$) vs. boron concentration (N_B) for the sublimation epilayers produced at increasing growth rate: 2 μm/h (1), 16 μm/h (2), 87 μm/h (3), 108 μm/h (4), 162 μm/h (5).*

The investigation indicates two acceptor levels associated with the presence of B in the 4H-SiC epilayers fabricated by two high-temperature techniques. A range of growth parameters to minimize boron incorporation in the layers and to control the preferred occupation of boron in the shallow or deep level is suggested.

[1] M. Syväjärvi, R. Yakimova, M. Tuominen, A. Kakanakova-Georgieva, M.F. MacMillan, A. Henry, Q. Wahab, E. Janzén, J.Crystal Growth 197 (1999) 155.
[2] A. Ellison, J. Zhang, J. Peterson, A. Henry, Q. Wahab, J.P. Bergman, Y.N. Makarov, A. Vorob'ev, A. Vehanen, E. Janzén, Mat. Sci. Eng. B61-62 (1999) 113.
[3] S.G. Sridhara, L.L. Clemen, R.P. Devaty, W.J. Choyke, D.J. Larkin, H.S. Kong, T. Troffer, G. Pensl, J. Appl. Phys. 83 (1998) 7909.
[4] V.I. Levin, Yu.M. Tairov, V.F. Tsvetkov, Sov. Phys. Semicond. 18 (1984) 747.
[5] T. Frank, T. Troffer, G. Pensl, N. Nordell, S. Karlson, A. Schöner, Inst. Phys. Conf. Ser. 142, 681 (1998).
[6] B. Aradi, A. Gali, P. Deák, E. Rauls, Th. Frauenheim, N.T. Son, Matrials Science Forum 353-356 (2001) 455.
[7] M. Bockstedte, A. Mattausch, O. Pankratov, Materials Science Forum 353-356 (2001) 447.

Impact of the initial surface conditions on the defect appearance in 4H-SiC epilayers

R. Yakimova, H. Jacobsson, M. Syväjarvi, A. Kakanakova-Georgieva, T. Iakimov, C. Virojanadara, L.I. Johansson, and E. Janzén

Department of Physics and Measurement Technology, Linköping University, SE-58183 Linköping, Sweden, tel. +46 13 28 25 28, fax: +46 13 14 23 37, e-mail: roy@ifm.liu.se

Progress in SiC-based technology has been made in many processes, e.g. 4H-SiC growth, ion implantation, metal contacts, etc. However control of the crystal quality during bulk and epitaxial growth is far from the desired. Control during epitaxial growth can be made more precise but inherence of threading defects from the substrate can not be avoided. Besides the threading defects emerging from the substrates (e.g. micropipes and dislocations), the epitaxial layers may develop specific defects, generally viewed as structural and morphological. Common defects in SiC epitaxy are stacking faults. They may act both as nucleation sites for polytype inclusions [1] and for degradation centres of device performance [2,3]. The surface morphology of the epitaxial layers is a critical characteristic since morphological defects may eventually hinder device processing [4]. While there is a growing body of experimental evidence pointing to a variety of harmful defects in SiC epitaxial layers, the origin and the nature of the defects are not completely understood and beg explanation. Finding the reasons for defect occurrence and eliminating them is a key issue in the SiC growth technology.

With this study we attempt an insight into extended defects generation in 4H-SiC epitaxial layers in respect to nucleation on different surfaces that may occur under two different conditions. One series of samples comprises as-grown surfaces obtained by liquid phase treatment of commercial substrates, made to reduce the micropipes. The micropipe healing was performed at TDI, Inc. [5]. A second series of samples was prepared by temperature treatment at 1700-2000°C in conditions resembling the initial phase of SiC growth via sublimation.

We have used SEM, electron emission, STM and SWBXT to characterise the initial surfaces and the layers grown on them by sublimation epitaxy. With increasing roughness of the nucleation surface, i.e. step width and step height, from 500nm, respectively 20nm, to 4μm, respectively 600nm, different types of defects are generated at the interface and are developed in the subsequently grown layers. With further increase of the surface roughness conditions for polytype switching have occurred.

Fig. 1(a,b) illustrates two distinguished cases. In the first case (a) stacking faults with accompanying partial dislocations, along with threading dislocations with $\mathbf{b} = 1/3\langle 11\bar{2}0\rangle$ are observed, while in the second case (b) misfit dislocations and dislocations in three (120°) symmetric directions are imaged. These results indicate that when the growth is disturbed, the easiest grown-in defect to be formed at the substrate/layer interface are partial dislocations and stacking faults, which is consistent with the low energy of formation of this defect. Edge dislocations due to a large "mismatch" were formed when the irregularity of starting surface exceeded some critical value. It is interesting to note that also interface related micropipes have

been observed to appear in the epitaxial layers, though this is not expected in the step flow mechanism. The result was obtained by KOH etching of the substrate and of the layer and the patterns characteristic of micropipes were compared.

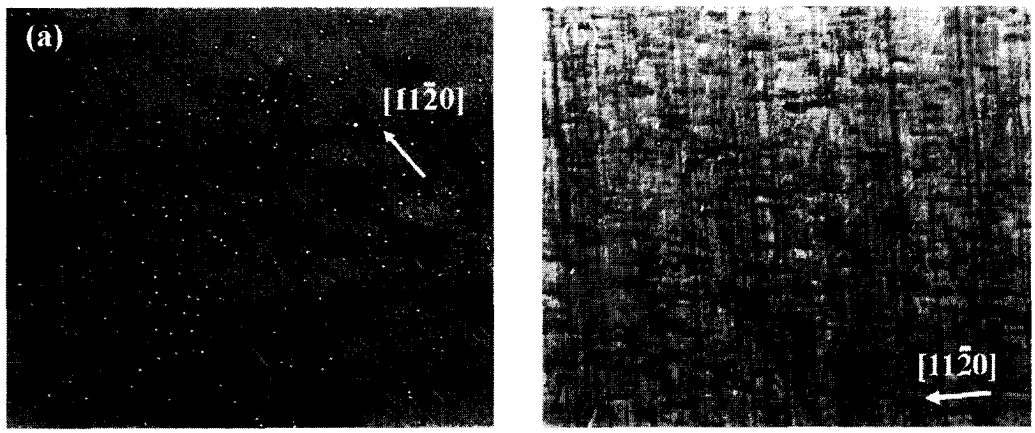

Fig. 1. Synchrotron white beam X-ray topography images of (a) stacking faults (triangular features) and (b) misfit dislocations (fine lines), in epitaxial layers grown on initial surfaces with increasing roughness.

The surfaces after the temperature treatment exhibit graphite coverage with thickness reaching 75 Å depending on the face polarity, as obtained by photo emission measurements. In contrary to the results presented in Ref. [6], this graphite is uniformly covering the substrate surface and is well ordered as proved by the LEED patterns. The STM images indicate step-wise morphology governed by the substrate off-cut. Growth on such surfaces was initiated and the results will be further discussed concerning the impact of the graphite film on the structural evolution during sublimation growth of 4H material. We have indications that the graphite film can be preserved during growth and thus to act as a two-dimensional defect in the grown layer.
Based on the experimental findings a thorough analysis of defect appearance in 4H-SiC layers will be made and a model for critical nucleation conditions of single 4H polytype will be presented.

References

[1] A.O. Konstantinov, C. Hallin, B. Pécz, O. Kordina, E. Janzén, J. Cr. Growth 178 (1997) 495.

[2] P.G. Neudeck, J. Electron. Mater. 24 (1995) 283.

[3] J.P.Bergman, H.Lendenmann, P.Å.Nilsson, U.Lindefelt, P.Skytt, Mater. Sc. Forum 353-356 (2001) 299.

[4] T. Kimoto, N. Miyamoto, and H. Matsunami, IEEE Trans. Electron Devices 46 (1999) 471.

[5] S. Rendakova, V. Ivantsov, and V. Dimitriev, Mater. Sc. Forum 264-268 (1998) 163.

[6] V.D. Heydemann, G.S.Rohrer, E.K. Sanches and M. Skowronski, Mater. Sc. Forum 264-268 (1998) 37.

HIGHLY UNIFORM EPITAXIAL SIC-LAYERS GROWN IN A HOT WALL CVD REACTOR WITH MECHANICAL ROTATION

A. Schöner[1], A. Konstantinov[1], S. Karlsson[2], R. Berge[3]

[1] *ACREO AB, Electrum 236, SE - 164 40 Kista - Stockholm, Sweden*
[2] *now at ADC, P.O. Box 911, SE – 175 29 Järfälla – Stockholm, Sweden*
[3] *Epigress AB, Ideon, SE-223 70 Lund, Sweden*
Phone: +46 8 632 7809 Fax: +46 8 750 54 30 E-mail: adolf.schoner @ acreo.se

Despite the improvements made over the past years in material growth of SiC, the epitaxial growth of highly uniform and pure layers is still an issue of development for the further commercialization of electronic devices made from SiC. The development focuses on high growth rates, purity, uniformity of layer thickness and doping concentration, and low crystal defect density. The hot wall CVD-reactor has proven to be a system for achieving high growth rates and pure layers. The thickness and doping uniformity is depending on the homogeneity of temperature and gas flow. Rotating the wafer during growth evens out possible temperature or gas flow inhomogeneities and more uniform layers can be grown.
We have developed a hot wall reactor with mechanical rotation based on the VP508 system, commercially available from Epigress, and the growth process for achieving SiC layers highly uniform in thickness and doping.

Figure 1 shows schematically the reactor design and the downstream side of the reactor in operation. The substrate lays on a satellite, which consists of tantalum carbide (TaC) coated graphite and is designed for 2" wafers. The satellite is loaded from the downstream side and placed on top of a graphite tube. The graphite tube can be moved vertical and rotates motor driven. The rotation speed is around 1 rpm.
The heating control in the reactor is done by a pyrometer, measuring the temperature above the satellite at the inclined ceiling of the susceptor (temperature maximum). The substrate temperature was calibrated by melting silicon on a SiC wafer. Silicon melted at a control temperature of 1520°C, indicating that the satellite is mainly heated by the radiation from the surrounding susceptor and not actively by the RF-field. Therefore, the susceptor has to be heated up to a much higher temperature to get the requested substrate temperature for achieving good quality SiC layers.

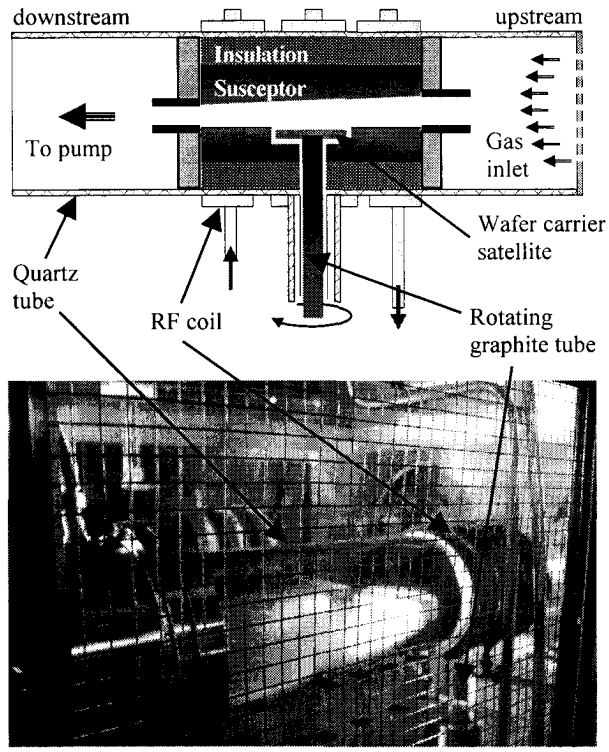

Fig. 1 Schematic drawing of the hot wall CVD reactor with mechanical rotation and the downstream side of the reactor in operation.

In our standard hot wall reactor the growth temperature is set to 1600°C, resulting in good layer morphology and low defect density. The substrate temperature is 50 to 100°C lower in the reactor with rotation. The lower substrate temperature does not affect the layer quality

in a negative way, which is probably due to that the supplied gases and the substrate surface are at a similar or higher temperature than in the standard reactor cell.
The epitaxial growth was done with a conventional precursor system of silane and propane. Nitrogen gas was used for n-type doping and trimethylaluminum (TMA) for p-type doping. The susceptor temperature was between 1650 to 1700°C, which corresponds to a substrate temperature of 1500 to 1550°C using the TaC-coated satellite. The total pressure in the reactor was set to 250 mbar. As carrier gas, hydrogen purified in a platinum cell as well as a mixture of purified hydrogen and argon was applied. Argon has a lower cooling efficiency than hydrogen and homogenizes therefore the temperature over the wafer area.

The thickness and doping characterization of the layers grown in the reactor with rotation was done mainly by capacitance voltage (CV) measurements and secondary ion mass spectrometry (SIMS). Figure 2 shows the results from CV-measurements on nitrogen doped epitaxial layers. The thickness uniformity is excellent with a standard deviation over mean value of 1% and a maximum variation over mean value of 4%, when excluding 5 mm at the wafer edge. However, the uniformity for both p- and n-doped layers grown with carrier gas hydrogen was not good. In n-doping we observed u-shape profiles with a concentration variation by a factor of 2 to 4. P-type doping showed camel like concentration distributions with a variation of about 25%. The reason for the large concentration variation is most likely related to the lower substrate temperature in combination with a cooling effect by incoming gases or the use of the TaC coated satellite.

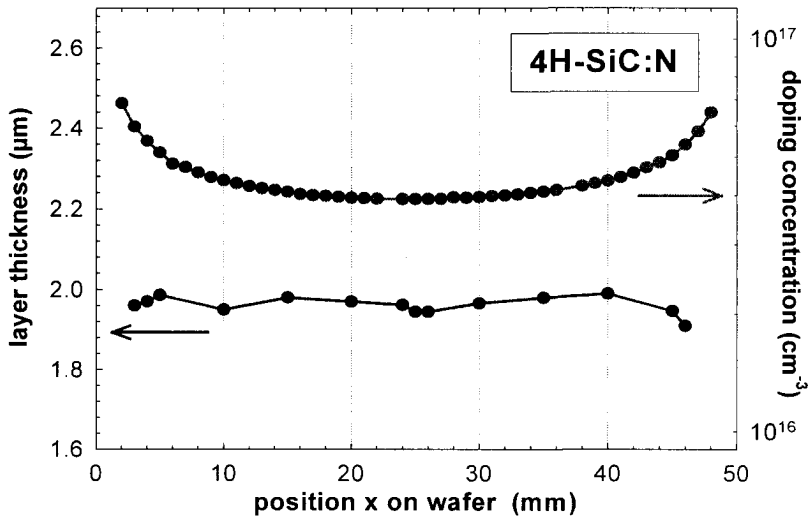

Fig. 2 Thickness and doping uniformity of n-type SiC layers grown in a hot wall CVD reactor with mechanical rotation.

From our standard hot wall reactor we have the experience that adding argon to the carrier gas gives a better layer uniformity. The same effect can be observed in the reactor with mechanical rotation. Adding around 15% argon to the hydrogen carrier gas by keeping the total carrier gas flow constant results in the doping distribution shown in figure 2. Excluding 5 mm at the edges of the wafer the concentration varies by 6% (standard deviation/mean) and 10% (maximum variation/mean).
In addition to the good thickness and doping uniformity, we observed in the reactor cell with rotation an increased growth rate in comparison to our standard hot wall reactor. Using the same precursor flows the growth rate is a factor of 1.5 to 2 higher, which is due to the lower substrate temperature in the reactor cell with rotation.

We have shown epitaxial growth of SiC with excellent thickness and doping uniformity using a hot wall reactor with mechanical rotation and a carrier gas mixture of 15% argon in hydrogen. The high uniformity of the layers gives rise to improved yield of devices, where the layer thickness and doping are critical issues.

Fast Epitaxial Growth of 4H-SiC by Chimney-type Hot-wall CVD

K. Fujihira, T. Kimoto and H. Matsunami

Department of Electronic Science and Engineering, Kyoto University, Sakyo, Kyoto 606 – 8501, *JAPAN*

Phone: +81-75-753-5341 Fax: +81-75-753-5342 e-mail: k-fuji@matsunami.kuee.kyoto-u.ac.jp

Owing to recent significant progress of SiC wafer quality and epitaxial growth technology, high-performance SiC devices have been reported. Although SiC device structures have been formed by CVD, a typical growth rate is relatively low, 2∼6 μm/h [1]. Vertical hot-wall CVD has merits such as high-temperature growth. High-temperature growth suggests a great potential of high-purity thick epitaxial growth with a high growth rate. One challenge in fast epitaxial growth so far is a relatively high concentration of deep levels, called the D_1 center, found as the L_1 center in the PL measurement [2, 3]. In this work, the authors realized high-speed epitaxial growth and found that the L_1 peak and the Z_1 center could be reduced in a growth under a C-rich condition.

Epitaxial growth was performed on off-axis 4H-SiC(0001) by vertical hot-wall chimney-type CVD in a SiH_4-C_3H_8-H_2 system at 1700°C. The H_2 flow rate and the reactor pressure was 3 slm and 100 Torr, respectively. All of source gases and carrier gas were introduced from the bottom end of reactor. The C/Si ratios were varied in the range from 0.6 to 0.75 with a fixed SiH_4 flow rate of 16.3 sccm.

The high growth rates of 22μm/h and 25 μm/h were attained with a mirror-like surface for the epilayers grown with C/Si=0.6 and 0.7, respectively. The Nomarski photographs of elilayers grown for 1 h showed excellent surface morphology without wavy pits and triangle defects. A relatively smooth surface without step bunching was observed by atomic force microscopy and a small surface roughness of 0.20∼0.25 nm was obtained (Table 1). Figure 1 represents the surface morphology and the height profile of epilayer grown with C/Si=0.7. The X-ray diffraction analysis revealed a FWHM of 14 arcsec, suggesting high quality of the epilayer. From *C-V* measurement, the net donor concentration was determined to be as low as 4×10^{14} cm^{-3} with C/Si=0.6 and 2×10^{14} cm^{-3} with C/Si=0.7. This result agrees with "site-competition epitaxy" [4].

Figure 3(a) shows a PL spectrum at 18 K for a 22 μm-thick epilayer grown with C/Si=0.6. Relatively strong free exciton peaks were observed, indicating its high purity and high quality. A relatively strong L_1 peak, the origin of which is considered to be an intrinsic defect complex, can be observed. Figure 3(b) depicts a PL spectrum at 18 K for a 25 μm-thick epilayer grown with C/Si=0.7. It is noticeable that the L_1 peak becomes weaker, suggesting that the origin of L_1 peak decreases under a C-rich condition. DLTS measurements revealed that the Z_1 center located at E_c-0.66 eV is the dominant trap. The Z_1 center concentration was 5×10^{13} cm^{-3} and 1×10^{13} cm^{-3} for epilayers grown with C/Si ratios of 0.6 and 0.7, respectively. Although the correlation between the Z_1 center (DLTS) and the L_1 center (PL) is still unopened question, the formation of both defect centers is suppressed under a C-rich condition.

Although off-axis SiC(0001) has been exclusively employed in growth and device fabrication, micropipe has been a severe obstacle. Recently, SiC(11$\bar{2}$0), which is equivalent to the cubic(110) and has a promise for the absence of micropipes and improvement

of MOSFET performance, has been investigated [5, 6]. The author's group proposes a novel crystal plane, 4H-SiC(03$\bar{3}$8), which has an inclination of 54.74° toward $\langle 01\bar{1}0 \rangle$ from 4H-SiC(0001), and is semi-equivalent to the cubic(001). Preliminary experiments on 4H-SiC(03$\bar{3}$8) yielded a net donor concentration of 1×10^{15} cm^{-3}. Comparison with the growth on off-axis (0001) will be discussed.

[1] O.Kordina et al., *Mat. Sci. Forum*, **264-268**, 97(1998).
[2] A.Ellison et al., *Mat. Sci. Eng.*, **B61-62**, 113(1999).
[3] H.Tsuchida et al., *Mat. Sci. Forum*, **338-342**, 145(2000).
[4] D.J.Larkin, *phy. stat. sol.* **(b)202**, 305(1997).
[5] H.Yano et al., *IEEE Trans. Electron Devices*, **46**, 611(1999).
[6] T.Kimoto et al., *Mater. Sci. Forum*, **338-342**, 189(2000).

Table 1 Parameters of 4H-SiC epilayers grown with C/Si=0.6 and 0.7.

C/Si	0.6	0.7
Growth rate (μm/h)	22	25
Rms (nm)	0.249	0.200
N_d (cm^{-3})	4×10^{14}	2×10^{14}
Z_1 center concentration (cm^{-3})	5×10^{13}	1×10^{13}

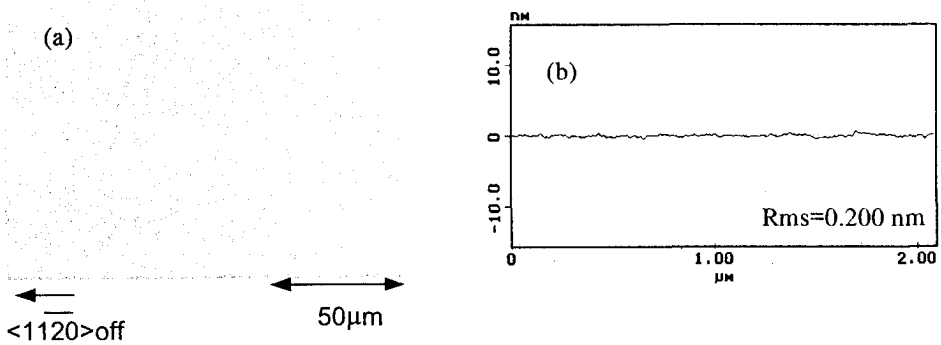

Fig. 1 (a)Nomarski photograph and (b) heigh profile of epilayer grown with C/Si=0.7.

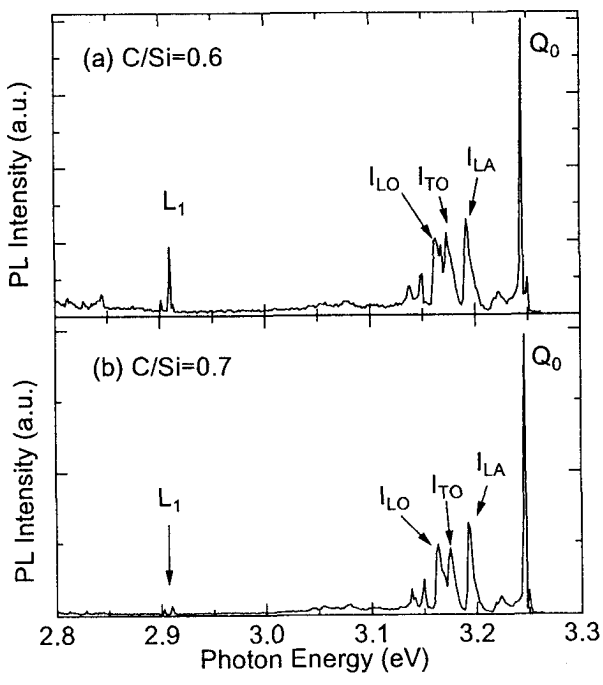

Fig. 3 PL spectra of 4H-SiC epilayers at 18K.
(a) C/Si=0.6, (b)C/Si=0.7

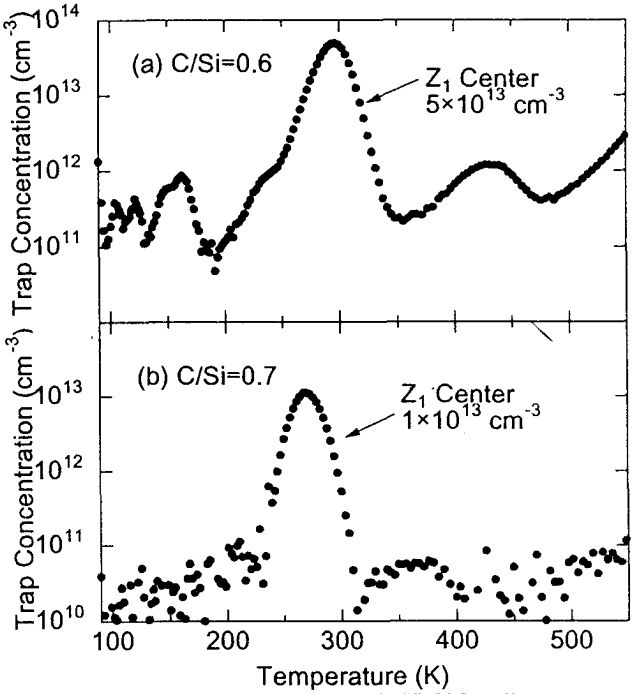

Fig. 4 DLTS spectra of 4H-SiC epilayers.
(a) C/Si=0.6, (b)C/Si=0.7

Growth and electrical characterization of the low-doped thick 4H-SiC epilayers

H. Tsuchida, I. Kamata, T. Jikimoto, and K. Izumi
Central Research Institute of Electric Power Industry,
2-6-1 Nagasaka, Yokosuka, Kanagawa 240-0196, Japan
Tel: +81-468-56-2121, Fax: +81-468-56-3540, E-mail: tsuchida@criepi.denken.or.jp

High-voltage SiC devices are attractive in the development of solid-state circuit current breakers and frequency converters for power transmission and distribution systems. Tens of kV SiC bipolar devices can be expected from the superior material constants of SiC, while successful results in obtaining a 12.3 kV SiC pin diode have recently been reported [1]. The growth of very thick epilayers, along with achieving a good morphology, low doping and long minority carrier lifetime, is a key technique to obtaining such ultra high-voltage SiC bipolar devices. This paper reports the growth and electrical characterization of low-doped thick epilayers in excess of 200 μm.

We used half sections or quarter sections of 8° off 4H-SiC(0001) wafers as substrates. Epitaxial growth of 4H-SiC was performed under a reduced pressure of 40-50 Torr in a vertical radiant-heating reactor, which consists of a vertical hot-wall and inner susceptor [2, 3]. Upward SiH_4+C_3H_8+H_2 gas flow was employed in the reactor. The growth temperature was 1530-1550℃ at the susceptor top, and the typical growth rate was 13-16 μm/h.

Atomic force microscopy (AFM) and Nomarski optical microscopy were used to investigate the morphology of thick 4H-SiC epilayers. Figure 1 shows an AFM image of a 246 μm-thick epilayer grown at 15 μm/h. No macro step bunching was observed, and the RMS roughness was determined as low as 0.20 nm by 10 μm x 10 μm AFM scanning. The surface was entirely specular, and the morphological defect density was less than 100 cm^{-2}. Figure 2 shows a low temperature photoluminescence (LTPL) spectrum taken from a 202 μm-thick epilayer. The LTPL spectrum shows strong free excitons and comparatively weak nitrogen bound excitons. Aluminum bound excitons and boron bound excitons are very weak.

To evaluate electrical characteristics of the thick epilayers, we fabricated Ni/4H-SiC Schottky barrier diodes (SBDs). Figure 3 shows C-V characteristics for three doping levels. From the $1/C^2$-V plots, the net doping concentrations (N_d-N_a) were determined as 1.7×10^{13} cm^{-3} for a 63 μm-thick epilayer, 6.7×10^{13} cm^{-3} for a 202 μm-thick epilayer and 4.3×10^{14} cm^{-3} for a 217 μm-thick epilayer. The $1/C^2$-V plots for the 202 μm-thick epilayer and the 217 μm-thick epilayer were fairly straight, however, the $1/C^2$-V plot for the 63 μm-thick epilayer curved at a low-voltage bias. In our DLTS measurements for epilayers doped to mid 10^{15} cm^{-3}, we found the Z_1 center with a density of $2\text{-}3\times10^{13}$ cm^{-3} in typical. For the 63 μm-thick epilayer, the doping concentration could be comparable to the Z_1 trap concentration. We also observed the L_1 line (D_1 center) from all samples used in this experiment by LTPL measurements. Influence of the deep levels (acceptor type) may be the reason for the bending of the $1/C^2$-V plot at a low-voltage bias.

In the forward I-V characteristics of the SBDs (Fig. 4), the specific on-resistance was 1.9 Ωcm^2 for the 202 μm-thick epilayer and 0.27 Ωcm^2 for the 217 μm-thick epilayer. This on-resistance implies high electron mobility with regard to the thickness and doping levels. The n-factors of 1.04 for a 1 mmϕ SBD (202 μm-thick epilayer) and 1.03 for a 0.5 mmϕ SBD (217 μm-thick epilayer) were obtained. On the other hand, the specific on-resistance of the 63 μm-thick epilayer was as high as 3.2×10^3 Ωcm^2, which corresponds to a resistivity of 5.1×10^5 Ωcm. We suppose that this rather high resistivity is a consequence of the reduction of background doping down to an equivalent concentration of the intrinsic defects.

In the reverse I-V characteristics (Fig. 5), the highest breakdown voltage of –6.3 kV was achieved for a 1.0 mmϕ SBD fabricated on the 202 μm-thick epilayer, even though no edge termination or surface passivation was processed. The leakage current density at –6.0 kV was 1.3×10^{-5} A/cm^2. Using the 217 μm-thick epilayer, the highest breakdown voltage of –6.4 kV was achieved for a 0.5 mmϕ SBD.

References
[1] Y. Sugawara, Extended Abstract of 1st Intern. Workshop on Ultra-Low-Loss Power Device Technology (May 31-June 2, 2000, Nara, Japan) pp. 133-139.
[2] H. Tsuchida, I. Kamata, T. Jikimoto, and K. Izumi, Mater. Sci. Forum, **338-342** (2000) 145.
[3] H. Tsuchida, T. Tsuji, I. Kamata, T. Jikimoto, H. Fujisawa, S. Ogino, and K. Izumi, Mater. Sci. Forum, **353-356** (2001) 131.

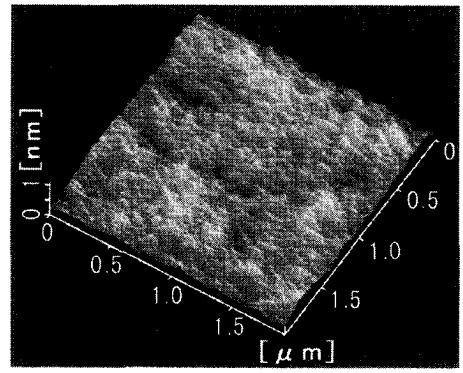

Fig. 1. AFM image of a 246 μm-thick epilayer (grown at 15 μm/h).

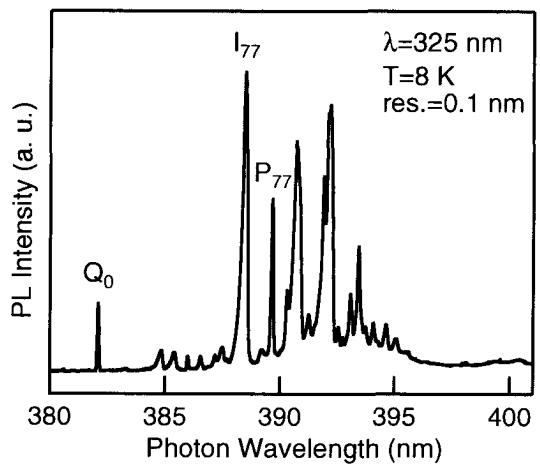

Fig. 2. LTPL spectrum taken from a 202 μm-thick epilayer (grown at 14 μm/h).

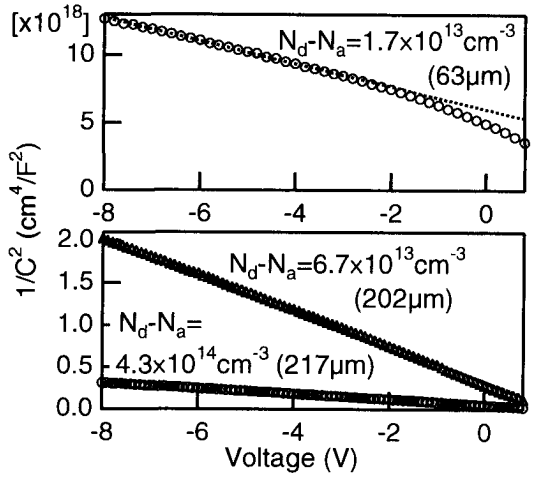

Fig. 3. C-V characteristics of Ni/4H-SiC SBDs fabricated on thick epilayers.

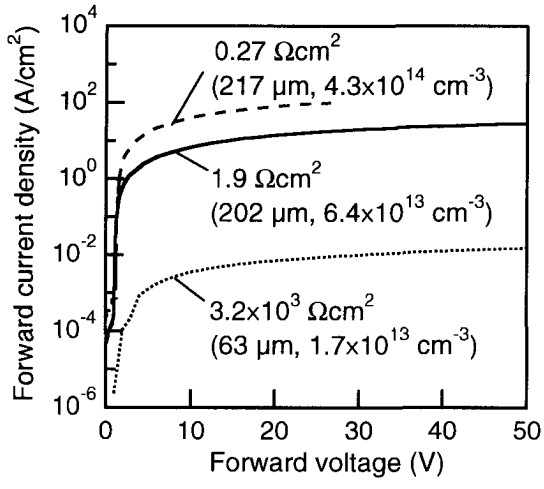

Fig. 4. Forward I-V characteristics of Ni/4H-SiC SBDs fabricated on thick epilayers.

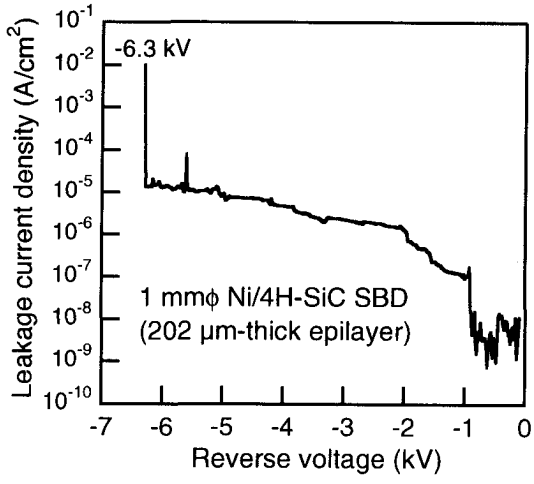

Fig. 5. Reverse I-V characteristics of a 1 mmϕ Ni/4H-SiC SBD fabricated on a 202 μm-thick epilayer.

High-Rate Epitaxial Growth of 4H-SiC using a Vertical-Type, Quasi-Hot-Wall CVD Reactor

K. Masahara[1], T. Takahashi[2], M. Kushibe[1], T. Ohno[1], J. Nishio[1], K. Kojima[1], Y. Ishida[2], T. Suzuki[1], T. Tanaka[1], S. Yoshida[2], and K. Arai[2]

[1] Ultra-Low-Loss Power Device Technology Research Body (UPR), R&D Association for Future Electron Devices (FED), 1-1-1, Umezono, Tsukuba, Ibaraki, 305-8568 JAPAN

[2] UPR, National Institute of Advanced Industrial Science and Technology (AIST), 1-1-1, Umezono, Tsukuba, Ibaraki, 305-8568 JAPAN

TEL:+81-298-61-5907, FAX:+81-298-61-5402, E-MAIL:koh@etl.go.jp

For power devices with high breakdown voltage, thick epitaxial layers are needed. If an epitaxial layer of 50 μm thickness is required, it takes more than 10-25 hours to grow when the growth rate is 2-5 μm/hr. This brings not only long process time but also increased consumption of substrate susceptor, which increases process cost. Therefore researches trying to obtain high growth rate of around 20-50 μm/hr have been done in recent years [1, 2]. We have obtained high growth rate of reaching about 70 μm/hr by using a vertical type, quasi-hot-wall CVD reactor. In this paper, growth conditions for obtaining high growth rate at relatively high temperature range (1600-1800 °C) are studied.

A vertical quasi-hot-wall CVD reactor which can set maximum a 75 mm diameter substrate wafer was used in this experiments. The process gases (SiH_4, C_3H_8, H_2) were distributed upwards through an inductively heated graphite nozzle. The 8° off-axis 4H-SiC (0001) substrates were attached to the susceptor so that the growth surface exposed downwards to the process gases. The growth temperature was in the range of 1600-1800 °C and the growth pressure was in the range of 2-760 Torr. The C/Si ratio was fixed to 1.5. The thickness of the grown layer was measured by observing the cleaved cross-section of substrates using scanning electron microscope. The etching rate was determined from the weight loss of the substrate using a microblance. The grown surfaces were examined with Nomarski differential interference contrast microscopy (NDIC).

Temperature dependence of the growth rate and the H_2 etching rate are shown in Fig. 1. The growth rate decreased with increasing the temperature in this range. The reason is that the H_2 etching rate increases exponentially with increasing the temperature. Pressure dependence of the growth rate and the etching rate at H_2 flow rate of 10 L/min are shown in Fig. 2. The etching rate (crosses in Fig. 2) dramatically decreased with increasing pressure. This result is qualitatively in agreement with the result using the vertical CVD reactor which we have previously reported [3]. The growth rate increased with increasing pressure in the lower pressure range of less than about 20 Torr (triangles). This may be explained in term of dramatic decrease in H_2 etching rate with increasing pressure [1, 4]. On the contrary, in the case of higher-pressure range of more than about 20 Torr, the growth rate decreased with increasing pressure (circles). This indicates that the species, which contribute to the growth, may be reduced with increasing the pressure. Figure 3 shows SiH_4 flow rate dependence of the growth rate at the pressure of 20 Torr. In this figure, solid symbols mean mirror-like surface morphologies, and open symbols mean rough surfaces. The growth rate increased with increasing SiH_4 flow rate. The grown surface, however, became rough when the SiH_4 was supplied excessively. The growth rate became low as the temperature became high. The growth rate of about 30 μm/hr was obtained at the temperature of 1800 °C and the SiH_4 flow rate of 36 cc/min when the H_2 flow rate was 10 L/min. Furthermore, the growth rate of 70 μm/hr was obtained at the same temperature and SiH_4 flow rate when the H_2 flow rate

was increased to15 L/min. Figure 4 shows the NDIC images of these grown surfaces. Fig. 4 (a) and (b) show the surface morphology of the epitaxial layer grown at the rate of 70 μ m/hr and 26 μ m/hr, respectively. Both surfaces were specular. However, the surface morphology of Fig. 4 (a) is rougher than that of Fig. 4 (b).

This work was performed under the management of FED as a part of the METI Project (R&D of Ultra-Low-Loss Power Device Technologies) supported by NEDO.

[1] A. Ellison et al., Material Science Forum Vol. 338-342 (2000) 131.
[2] T. Kimoto et al., Jpn. J. Appl. Phys. Vol. 40 (2001) L374.
[3] K. Masahara et al., Material Science Forum Vol. 338-342 (2000) 1037.
[4] M. Kushibe et al., Material Science Forum Vol. 338-342 (2000) 169.

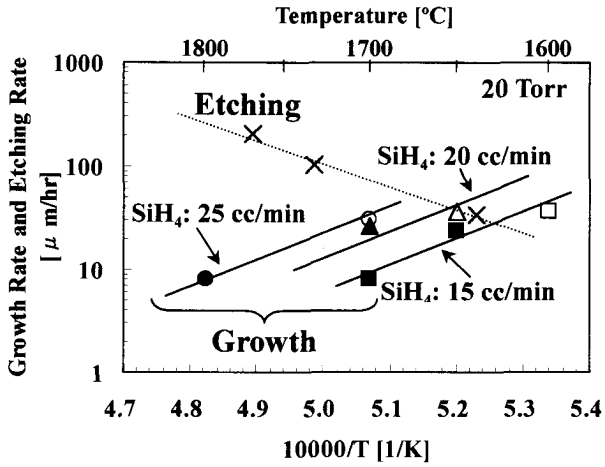

Fig. 1. Temperature dependence of growth rate and etching rate. Crosses mean etching rate. Circles, triangles, and squares mean growth rate. Solid symbols mean mirror-like surfaces and open symbols mean rough surfaces. The pressure is 20 Torr at all conditions.

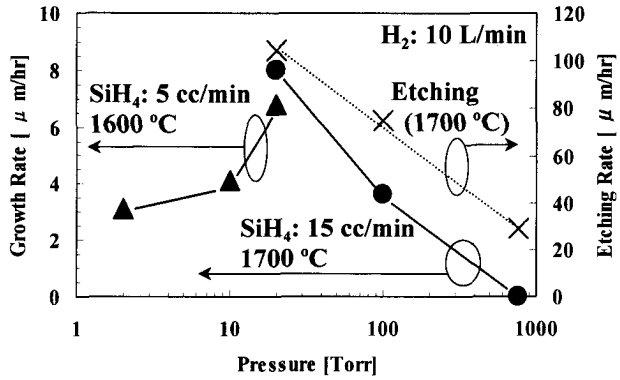

Fig. 2. Pressure dependence of growth rate and etching rate. Crosses mean etching rate. Circles and triangles mean growth rate. The condition is SiH_4 of 5 cc/min, temperature of 1600 °C for triangles and SiH_4 of 15 cc/min, temperature of 1700 °C for circles. The H_2 flow rate is 10 L/min.

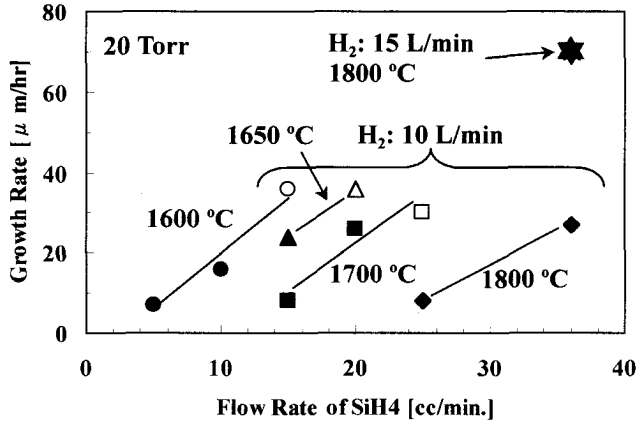

Fig. 3. SiH_4 flow rate dependence of growth rate. The H_2 flow rate is 10 L/min for circles, triangles, squares, and diamonds and 15L/min for a star. Solid symbols mean mirror-like surfaces and open symbols mean rough surfaces. The pressure is 20 Torr at all conditions.

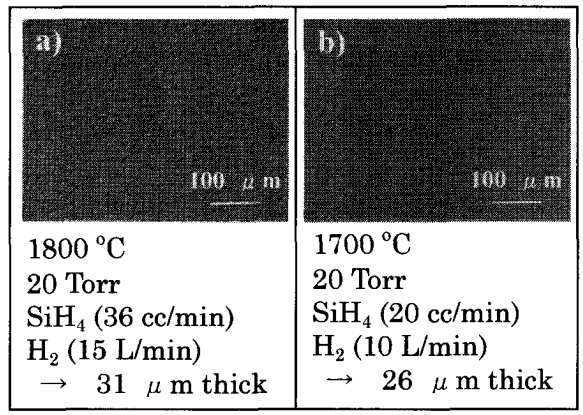

Fig. 4. Examples of NDIC images of the grown surfaces. The growth rate is 70 μ m/hr for a) and 26 μ m/hr for b).